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RESEARCH EXPERIENCE FOR UNDERGRADUATES IN ROBOTICS AND MATERIALS

WRIGHT LABORATORY

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March 1993

Final Technical Report for Period September 1991 to December 1992

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13. ABSTRACT

Florida International University successfully completed the proposed project entitled, "Research Experience for Undergraduates in Robotics and Materials." Nineteen students designed and manufactured a "user-friendly" industrial robot with three functional axes and an IBM-PC-based controller. The accuracy of the robot is 0.0005 inch when two axes are used. An operator can control the motions of the robot with a few hours of training by using the PC-based controller mouse. The controller also provides graphical simulation of the robot motions.

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1. INTRODUCTION

Florida International University (FIU) completed the design and manufacture of the robot outlined in the study entitled, "Research Experience for Undergraduates in Robotics and Materials." The major accomplishments, design of the robot, its controller, and related studies are outlined in this report.

2. MAJOR ACHIEVEMENTS

The major achievements and tasks that were accomplished in this project can be stated in the following three categories: Research/Development, Educational, and Industrial Achievements.

2.1 Research/Development Achievements

1) A prototype for the proposed robot manipulator was constructed and demonstrated successfully. Following are the special configurations and advantages of this robot:
   - This robot was designed using the skew photograph, such as a hybrid of closed-chain and open-chain mechanisms, which enables the robot to provide a greater payload and higher degree of accuracy.
   - With careful calculation of the direction of the two control actuators, this robot manipulator provides two separate straight-line motions parallel to the horizontal and vertical, while activating only one actuator. Nevertheless, combined activation of these two control actuators will produce a curvilinear trajectory.
   - A simple experiment was conducted and demonstrated that this prototype has a very high repeatability and accuracy (precision) with an error less than 0.0005 inches when two axes are used.
   - Wide application of this prototype to industrial, environmental, military, and medical usage is being considered and discussed.
2) An **Advanced Robotics Laboratory** and **Mechatronics Laboratory** for the purposes of research, development, and education (teaching/experiment) was developed as a result of this research project. Continuation of this project will be critical for the growth and development of these laboratories.
3) Several research papers were published and more papers are being prepared.

2.2 Educational Achievements

a) A total of 19 undergraduate/graduate students (both part-time and full-time) have been supported throughout this project with tuitions and/or assistantship. The students who received support are listed below: Christine Mekdeci, LeAnn Kunce, Petra Tober, Jeffrey Daniels, Bernando Donoso, Carlos Buxton-Gonzalez, Alejandro Souto, Leonel Peralta, Robert Rojas, Eduardo Paz, Moshe Annuar, Brian Faleiro, Frank Dopico, Luis Jimenez, Ellson Vallidum, Andrew Lyew, Hsien-Kuez Tseng, Kichol Lee, and David Katz.

b) The students formed an "Intelligent Robot Development Team" (IRDT) to take part into the design, manufacture, control, analysis, experiment, and drafting of the prototype of the robot manipulator. Management of the student group proved to be successful, and provided invaluable experience for the continuation of similar projects.

c) This project was associated with the required undergraduate course, "Senior Design Project," which is also a requirement for the graduation of many members in the IRDT. Three senior design projects will be presented in the areas of design/analysis, computer control/simulation, and experiment/Finite Element Analysis (FEA).

d) At the present time, three undergraduate students in the IRDT decided to continue with their studies toward the masters degree. All three students have expressed great enthusiasm and interest in continuing their current robotics research. Consequently, continuous support of this project will provide a great opportunity to advance the research capabilities and careers of the students. Interviews with these students can be arranged upon request.

e) One graduate student, under the supervision of Dr. T. C. Yih, is conducting the kinematic analysis, dynamic analysis, and computer simulation for this prototype. Completion of this research will lead him to the fulfillment of his Masters degree.

f) Two new courses are to be proposed to the Curriculum Committee for permanent implementation into the Design Program in the Mechanical Engineering Department. There will be one course at the undergraduate level: "EML 4xxx - Introduction to the Mechanical Design of Robots," and one at the graduate level: "EML 5xxx - Intermediate Design of Robots." These two courses will provide basic knowledge in the design/analysis of robot manipulators for students before attending the existing graduate course, "Advanced Design of Robots."

g) This project provided the students with hands-on experience on the design, control, and manufacturing of a robot. They also learned the importance of teamwork and team spirit. The success of this project definitely enhanced and advanced their knowledge and research capabilities in robotics studies.

2.3 Industrial Achievements

a) An association between Dr. Yih and an industrial partner [Mr. Phil Perry: (305) 255-2860 (office); (305) 251-2822 (Fax)] was established. Also, Dr. Tansel established affiliations with Anilam Electronics and Southern Gear and Machine Inc. An NSF grant was received to prepare a joint project with Southern Gear and Machine Inc.

b) Mr. Perry is seeking potential investors and partners who believe that the future is in robotics applications in manufacturing and that they will enhance the quality and competitiveness of the manufacturing industry in the United States.

3. DESIGN GOALS OF THE ROBOT

In this project, a new robot design was considered. The design criteria were set to achieve the following goals:

1. The robot should have a large (load capacity/weight) ratio.
2. The robot should be easy to control.
3. The designed configuration should simplify the task of the controller to move the robot tip on a straight line.
4. The actuators should be kept at the base to be able to easily shield them in hostile environments.
5. Modification of the robot structure should be easy and various sensors should be easily installed on the robot. Manufacture of the final structure will be started.

4. DESIGN AND MANUFACTURE OF THE ROBOT

4.1 Material Selection

Use of aluminum and composite materials were considered. Aluminum was preferred since it is easy to be machined and the structure can be modified easily to add various sensors. The initial studies indicated that a composite body would be lighter but it would not be convenient to prepare the prototype. A composite body would not allow design changes after the parts were manufactured and installation of sensors would be very difficult to collect experimental data.

4.2 Design of the Robot

First, the robot arms were considered as rigid bars and the motions of the robot were studied with a simulation program. The optimum arm lengths and angles had a straight line motion capability (in the horizontal and vertical directions) by using only one axis. The simulation studies are included in Appendix A. The detailed design of the robot was prepared to simplify the manufacturing process. All the parts of the robot were designed and machined by FIU students (except one shaft, which required a turning operation).

4.3 Finite Element and Simulation Analysis of the Main Robot Arm

Four elements of the proposed robot are identical and they carry the weight. The load distribution on these elements were studied by using the FEA (Finite Element Analysis) package, *ANASYS*, on a Sun Workstation (Appendix B). FEA indicated that the designed parts would allow the robot to carry over 100 pounds of weight without having any problems.

Also, sketches for the robot at various positions were simulated (Appendix B) to evaluate the work area of the robot.

4.4 Final Design of the Robot

Detailed dimensions for the fabrication of necessary parts to assemble the robot manipulator are provided in Appendix C. The drawings include: robot assembly; assembly of the major linkages; supporting plates for actuators, 1 and 2; lateral supporting plates (1, 2, 3, and 4); base assembly; and brackets, 1 and 2.

5. CONTROLLER DESIGN

An intelligent controller was developed for the robot. The controller has the following capabilities:

- It is written in the C-Language for minimal program size (executable version) and to easily access all the hardware.
- It controls three DC servo motors simultaneously.
- It accepts inputs from a keyboard or mouse. It displays the position of the robot graphically on the screen.
- It is compatible to work with a neural network-based motion control program.

The controller program and its explanation are presented in Appendix D.

Also, various studies were completed on neural network-based control of robots. A neural network-based graphics program was also developed to simulate the four-bar mechanism by using neural networks.

6. STUDIES ON SHAPE MEMORY ALLOYS

Shape memory alloys can generate the linear motions required by the designed robot. An extensive computer literature search on shape memory alloys was accomplished and about 134 articles were reviewed. Use of Nitinol wires were promising for generating the motions, if a miniature version of the robot is developed.

7. DEMONSTRATION

The robot and controller were demonstrated for Ms. Linda Sny when the two axes of the robot were functional. The repeatability and precision of the robot were found better than 0.0005 inches in the experiments.

8. CONCLUSION

The Intelligent Robot Development Team (IRDT) members completed the design and manufacture of the proposed robot. All of the goals of the proposed work were achieved.

The developed robot can be used for many industrial applications or special purpose tasks.

PUBLICATIONS

A number of publications were written during the project. Some of the papers are listed in Appendix E.

APPENDIX-A

CONCEPTUAL DESIGN AND PROOF OF THE PANTOGRAPH DESIGN OF THE WPAFB ROBOT

A. PROOF OF THE PANTOGRAPH DESIGN OF THE WPAFM ROBOT

A.1 Introduction

A robot manipulator is usually considered as a chain of links connected by revolute or prism joints. The programming of a manipulator is essentially to control the position and orientation of the end effector. Since the position of a point is determined by three independent data, X-position, Y-position, and Z-position. Therefore, the manipulator generally needs three degrees of freedom to bring the end effector to any desired position. Usually, the manipulator's end effector has three additional degrees of freedom to orient it. Thus, at least six joints are needed for general purpose manipulators.

A robot can be considered either an open-loop or a closed-loop mechanical system. Open-loop manipulators is one in which the last link end is free in space, as opposed to closed-loop manipulators in which the last end is fixed.

Our design is a combination of these two systems. In this way, we can use the most effective and useful part of each system for a better and improved design. The pantograph mechanism can provide us with this particular system.

Pantograph history can be traced back to the seventeenth century. Since then, pantographs were used extensively in embroidering machines, copying machines, and magnifying mechanisms. In the nineteen century, a more general form of the pantograph, the SKEW pantograph or Plagiograph, which was called by *its inventor*, was introduced by Sylvester. Both the pantograph and the skew pantograph are planar mechanisms. The skew pantograph is the base of the well known Roberts' theorem of cognates. Roth applied the skew pantograph to his study of cognates. Although pantograph mechanisms have been in use for a long time, the literature and study available on the geometric design of the pantograph is surprisingly sparse.

A.2 The Pantograph Design

With reference to Fig. A.1, a pantograph design for the WPAFB robot is proposed. This manipulator is composed of one 4-bar parallelogram mechanism (BCDE), and two identical ternary linkages, ABC and CDF. The gripper will be attached to the end-effector, F, at which two orthogonal motion trajectories can be generated with appropriate control at joints, A and E.

Such a pantograph design will provide the following advantages:

(1) a higher payload capacity;

(2) higher control precision;

(3) relatively simple structure for manufacturing and constructing the prototype.

A.3 Proof of the Pantograph Design

Consider the two triangles, ΔABE and ΔEDF, in which

$$BA = BE = CD \text{ and } \qquad DE = DF = BC.$$

Also,

$$\angle ABC = \angle CDF = \text{Const.},$$

by parallelogram,

$$\angle B_3 = \angle D_3.$$

Therefore, $\angle B_2 = \angle D_2$ $(= \angle ABC - \angle B3 = \angle CDF - \angle D3)$,

and $= \angle B1 = \angle D1$.

From ΔABE, $\angle A = \angle E1$.

Also from ΔEDF, $\angle E2 = \angle F$.

Known $\angle D_2 = \angle B_2$.

Therefore, $\angle E_2 = \angle F = \angle E_1 = \angle A$.

In this case, ΔABE and ΔEDF are similar triangles,

and:

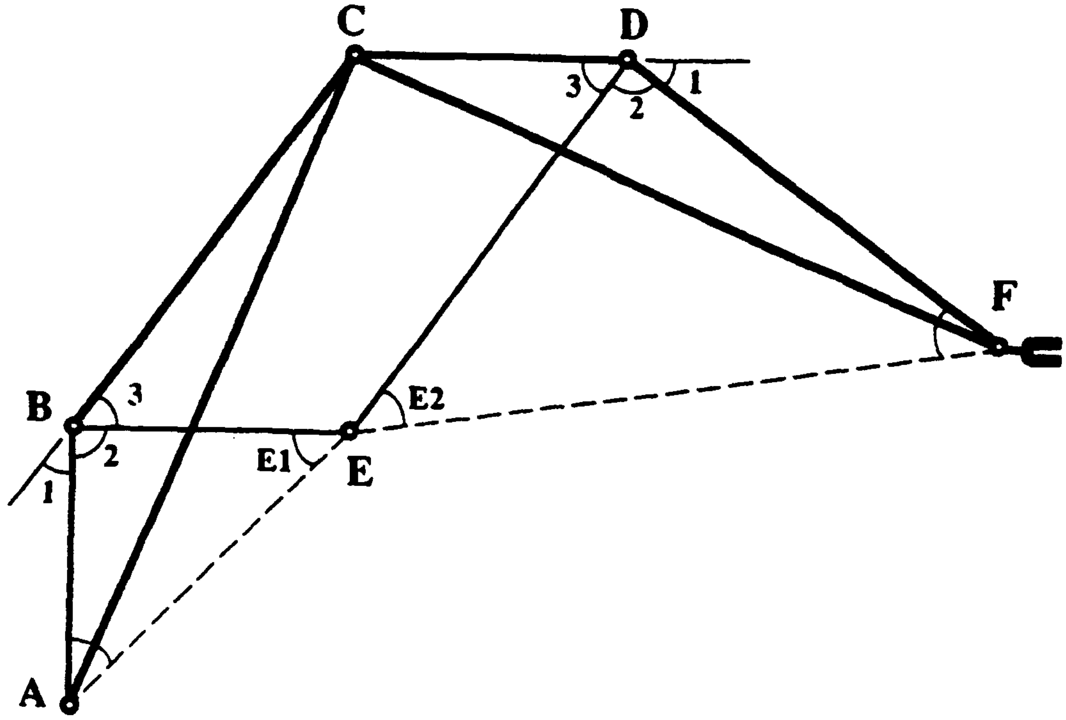

Fig. A.1 Pantograph Structure of the WPAFM Robot Manipulator.

$$\frac{AE}{EF} = \frac{BE}{DE} = \frac{AB}{DF}$$

where $\frac{BE}{DE}$ is constant in any case.

Therefore, $EF \cdot BE = AE \cdot DE$.

Also, $AE = EF \cdot \frac{BE}{DE}$,

or $EF = AE \cdot \frac{DE}{BE}$,

where AE is the input length, and EF is the final length.

Finally,

$$\frac{EF}{AE} = \frac{DE}{BE} = \frac{DF}{AB} = R = \text{Const.}$$

The designed structure is proven to be a pantograph.

APPENDIX-B

FINITE ELEMENT AND SIMULATION ANALYSIS OF THE ROBOT ARM

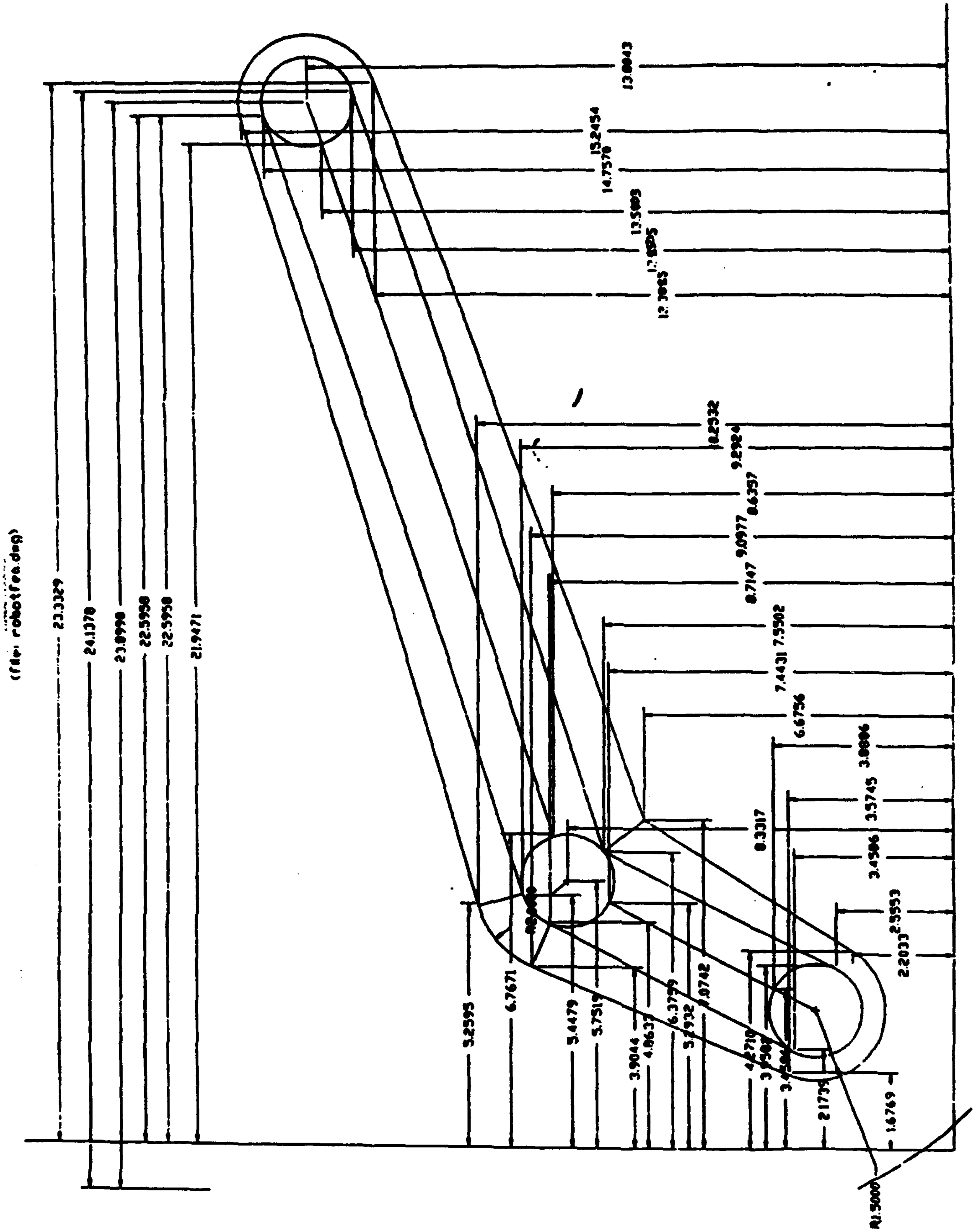

Figure B-1. Robot Main Link Sketch for FEA Modeling

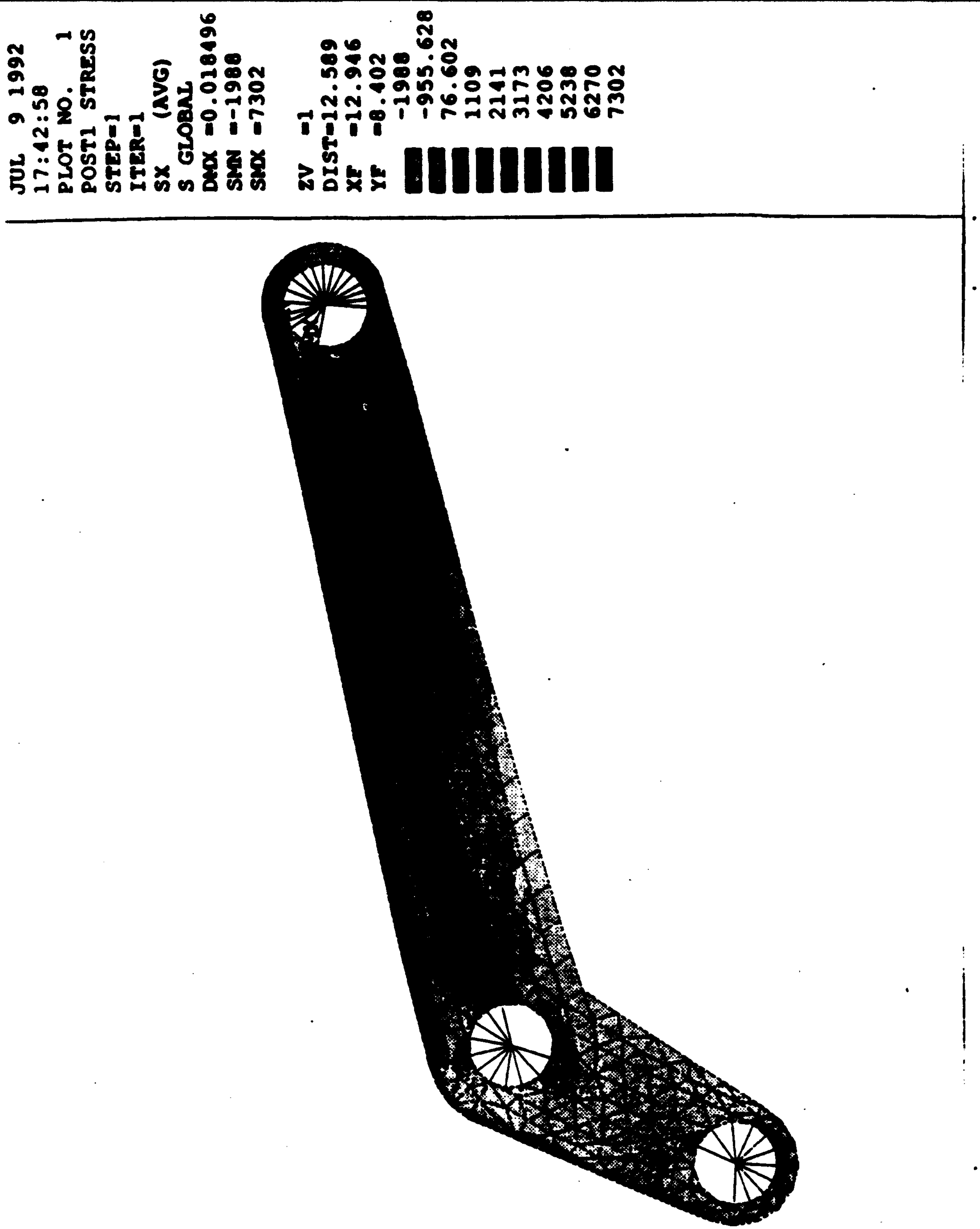

Figure B-2. Robot Main Linkage Static Model

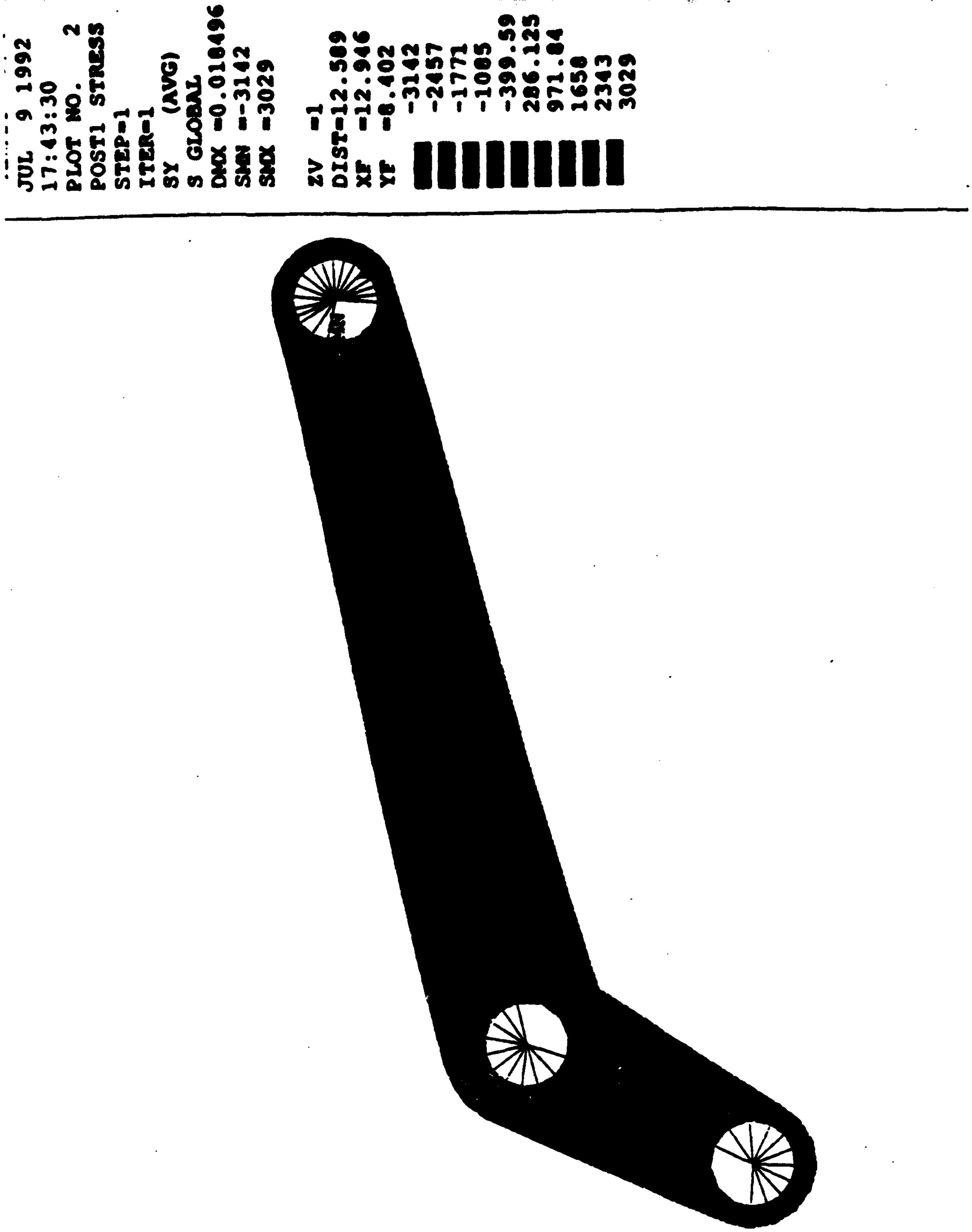

Figure B-3. Robot Main Linkage Static Model

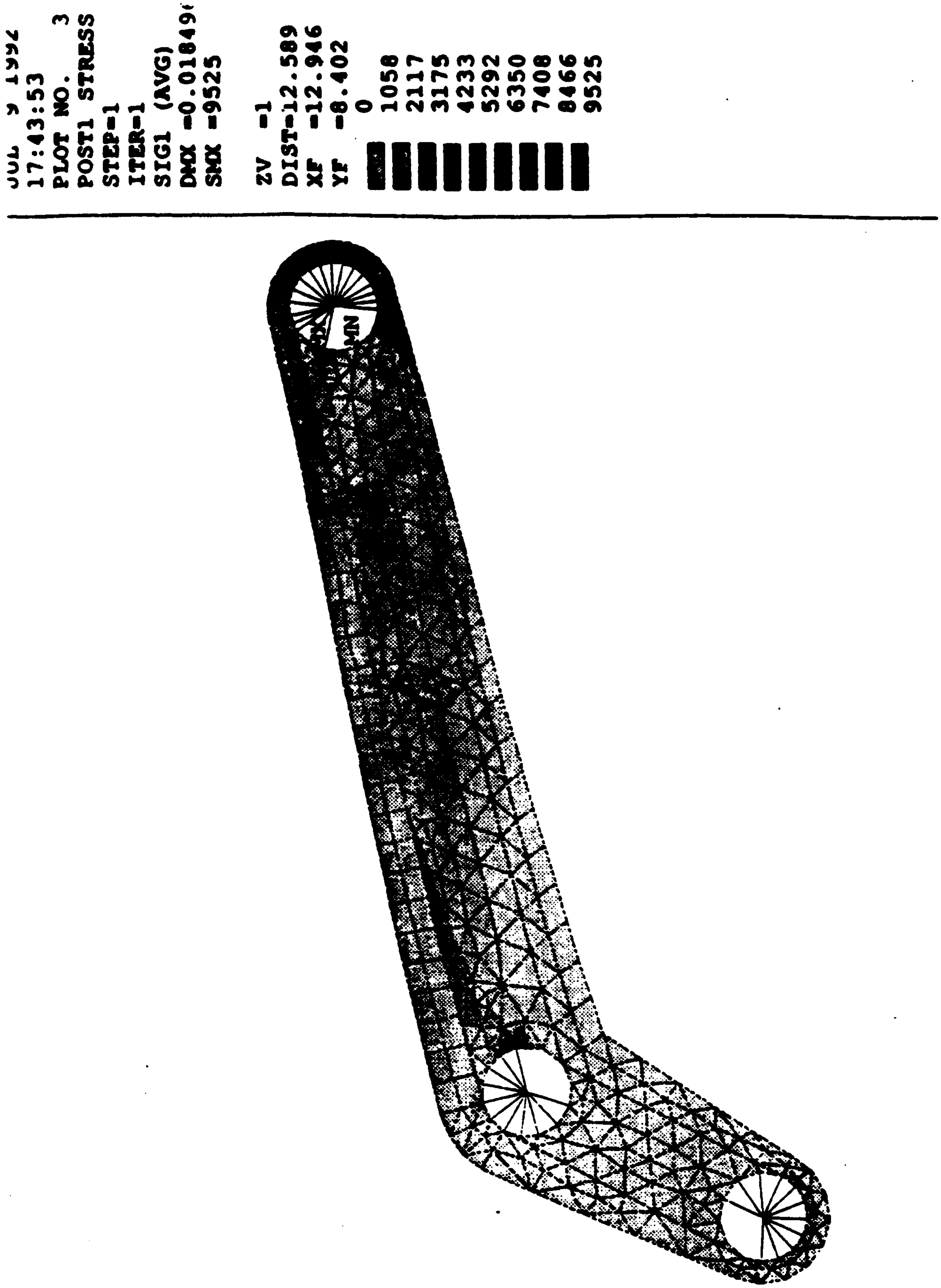

Figure B-4. Robot Main Linkage Static Model

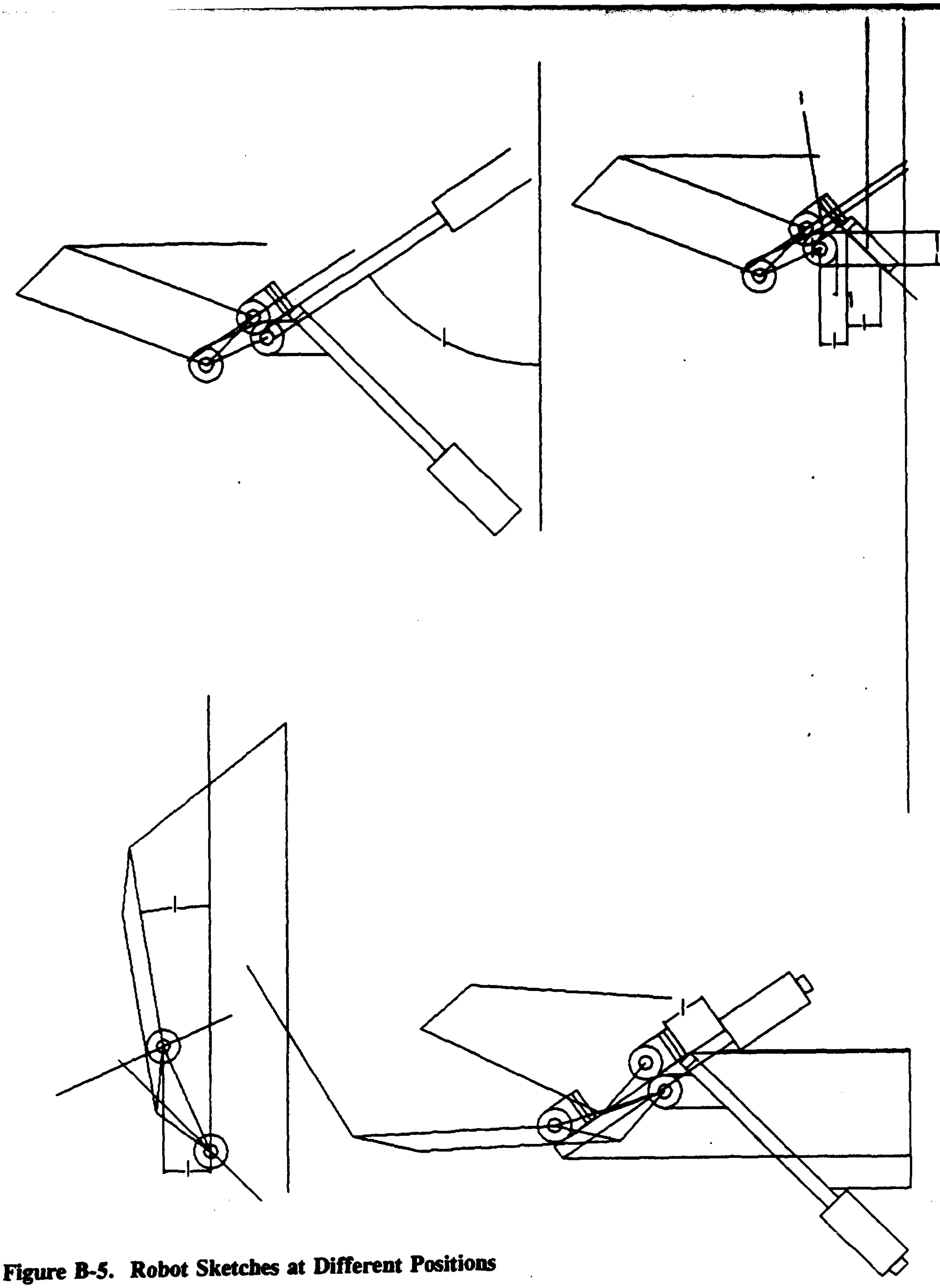

Figure B-5. Robot Sketches at Different Positions

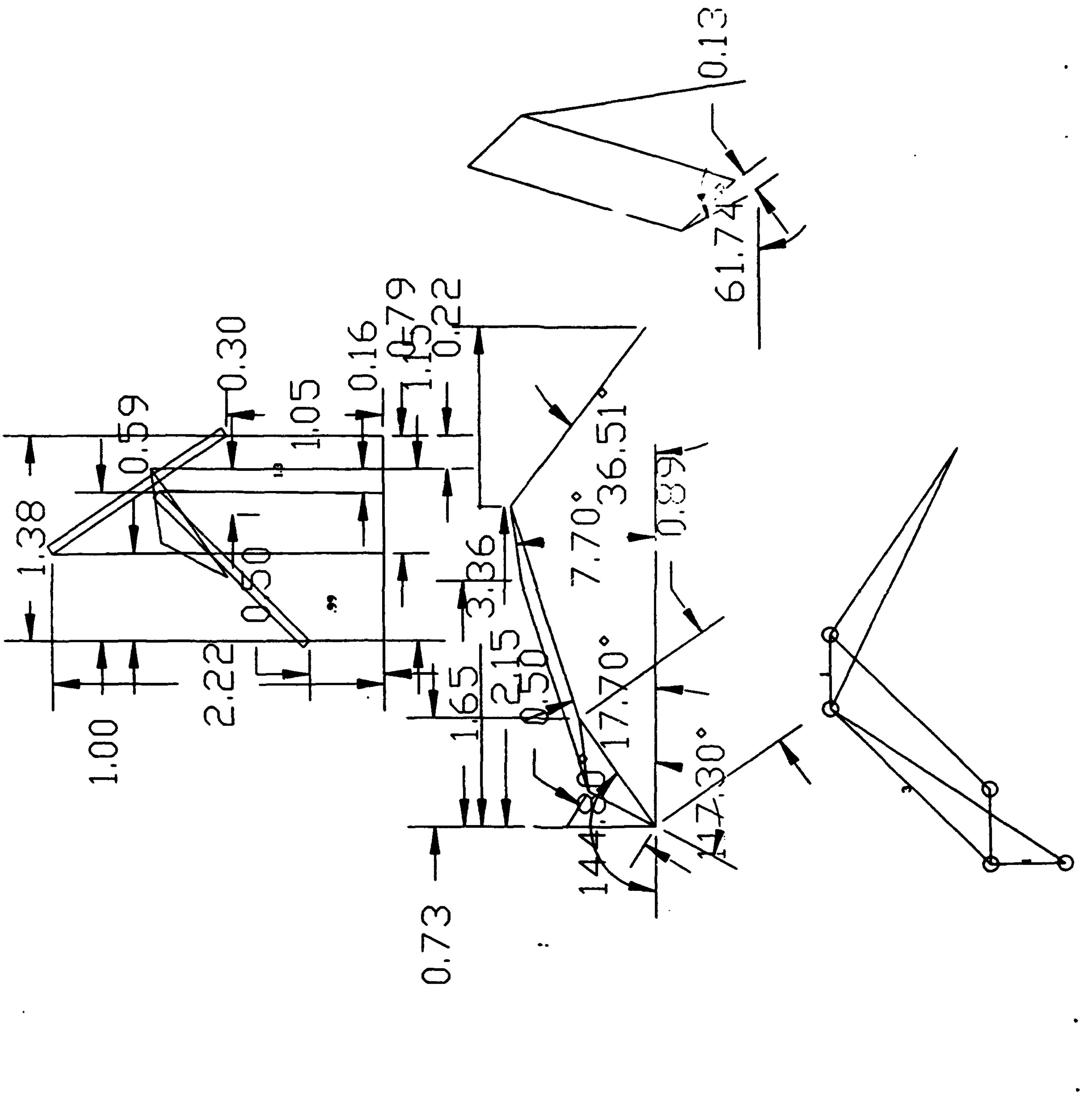

Figure B-6. Robot Sketches at Different Positions

APPENDIX-C

ASSEMBLY OF THE ROBOT MANIPULATOR

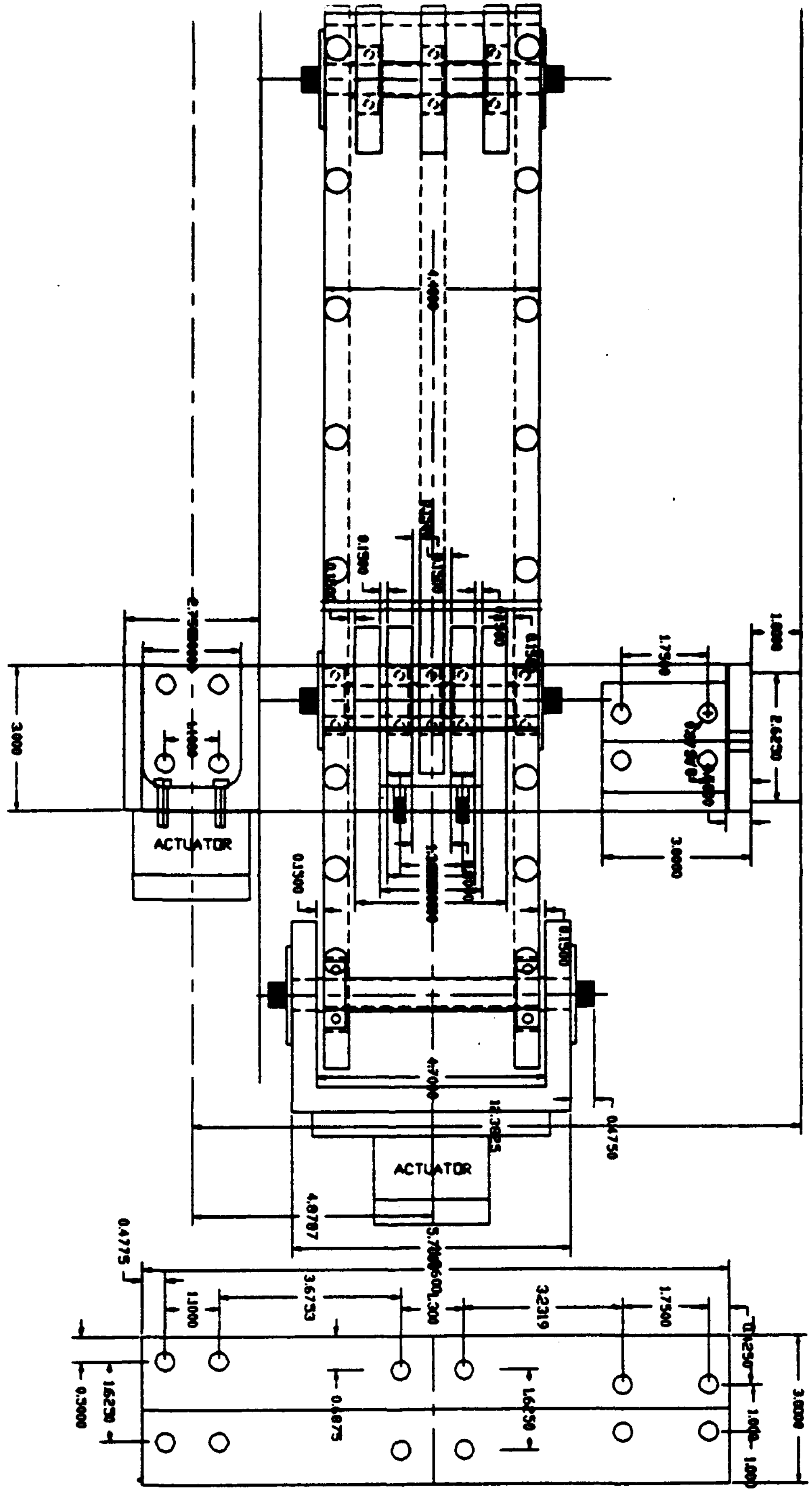

Figure C-1. Robot Assembly

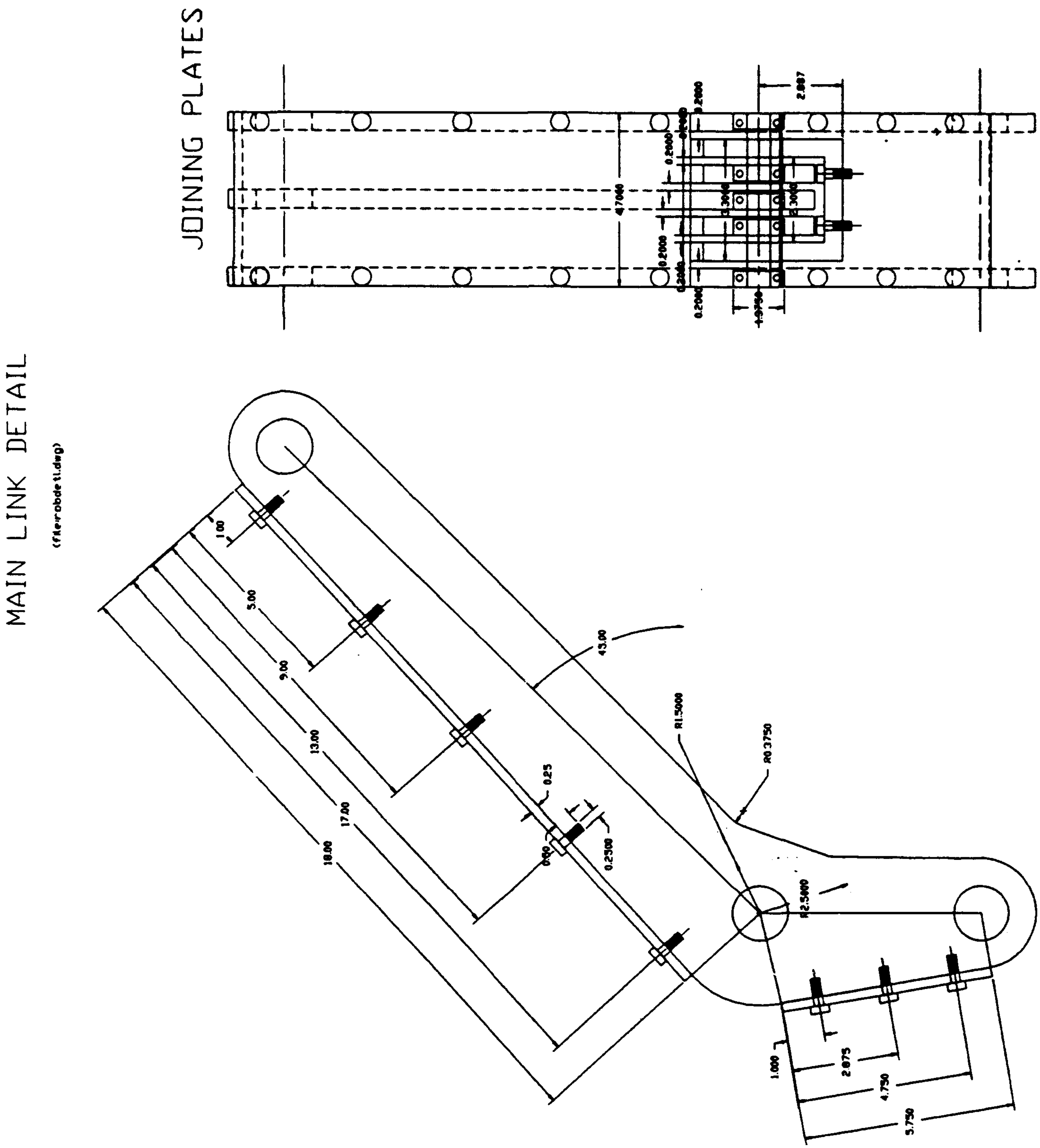

Figure C-2. Main Link Detail

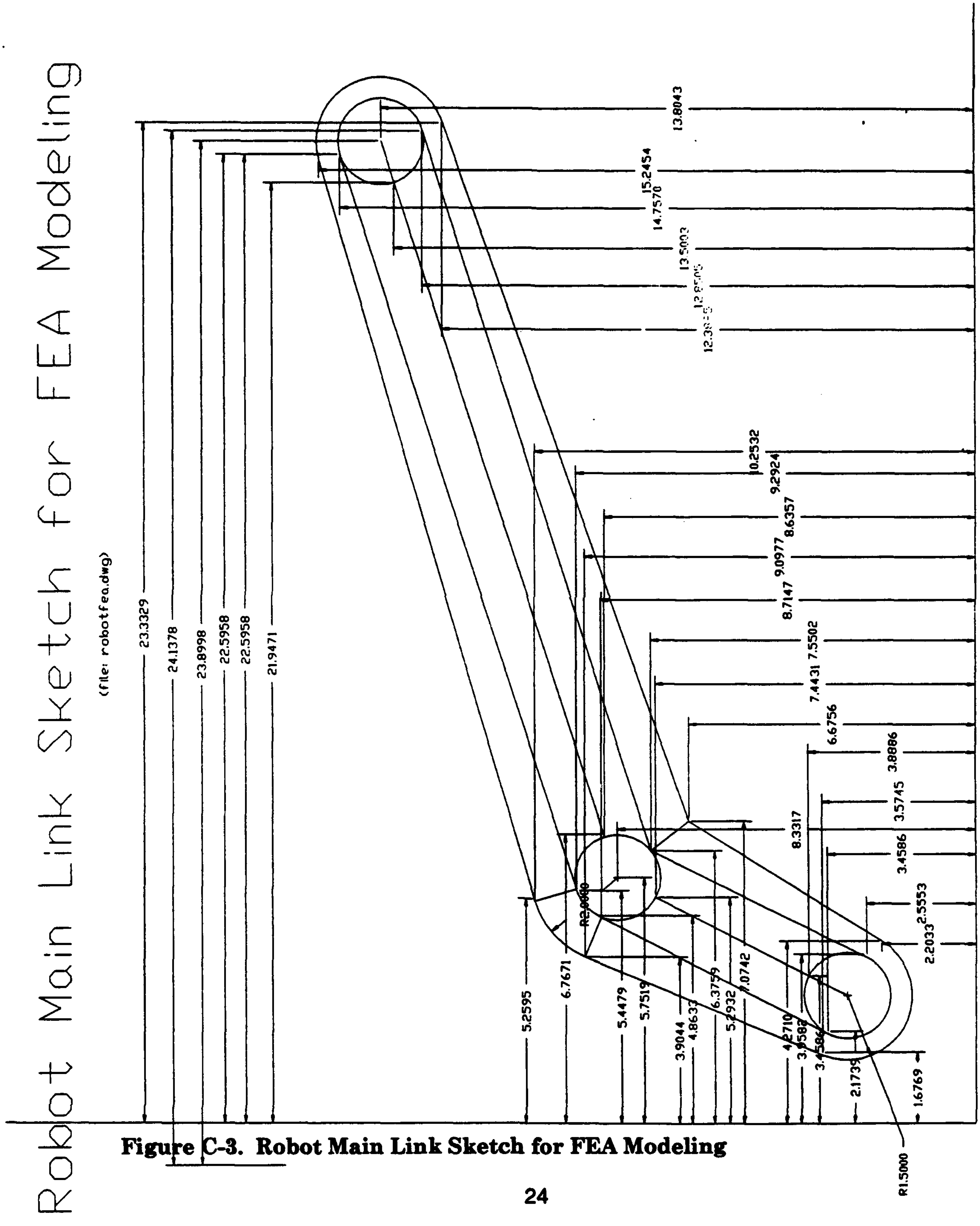

Figure C-3. Robot Main Link Sketch for FEA Modeling

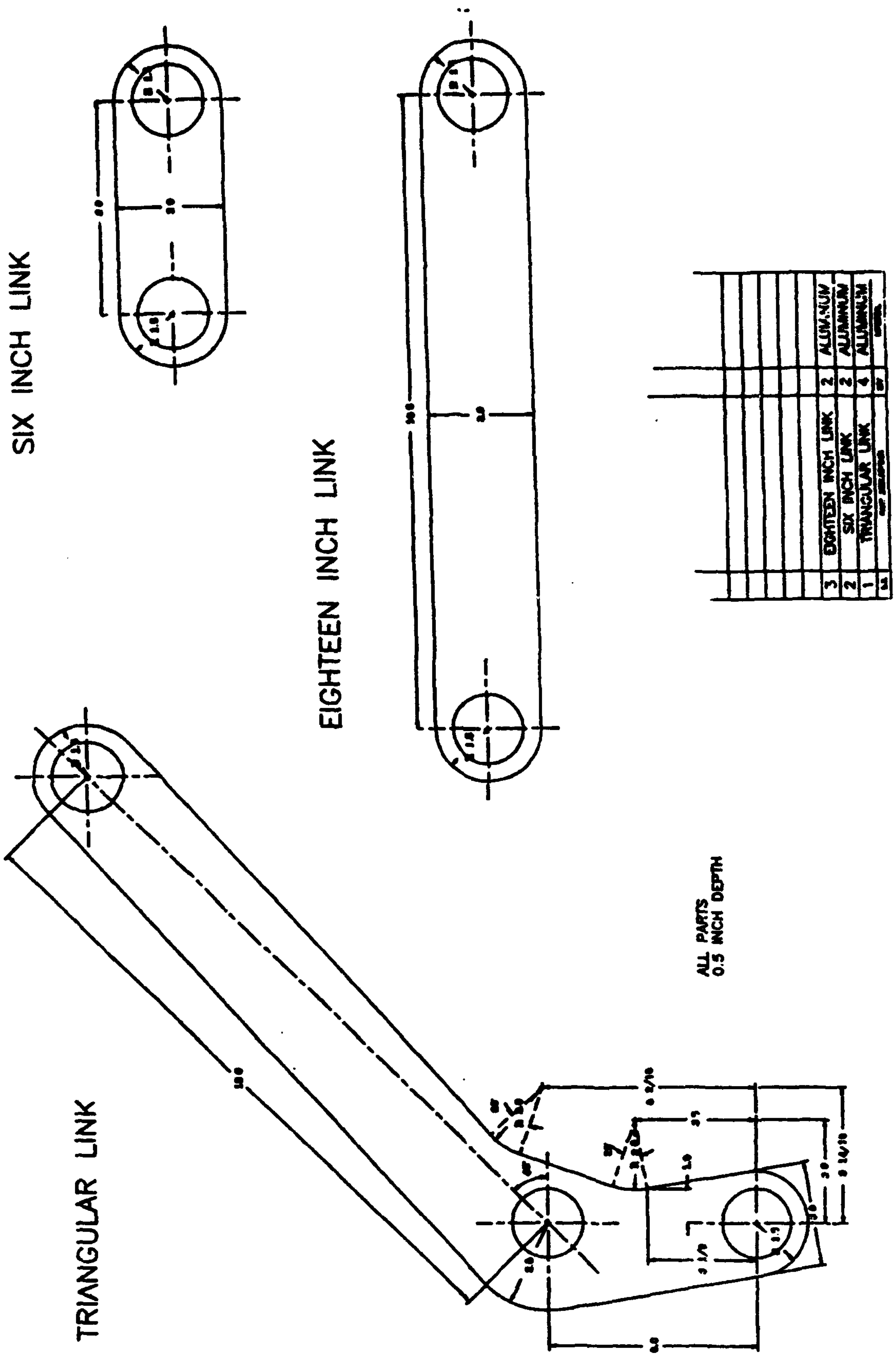

Figure C-4. Drawing of Robot Arm

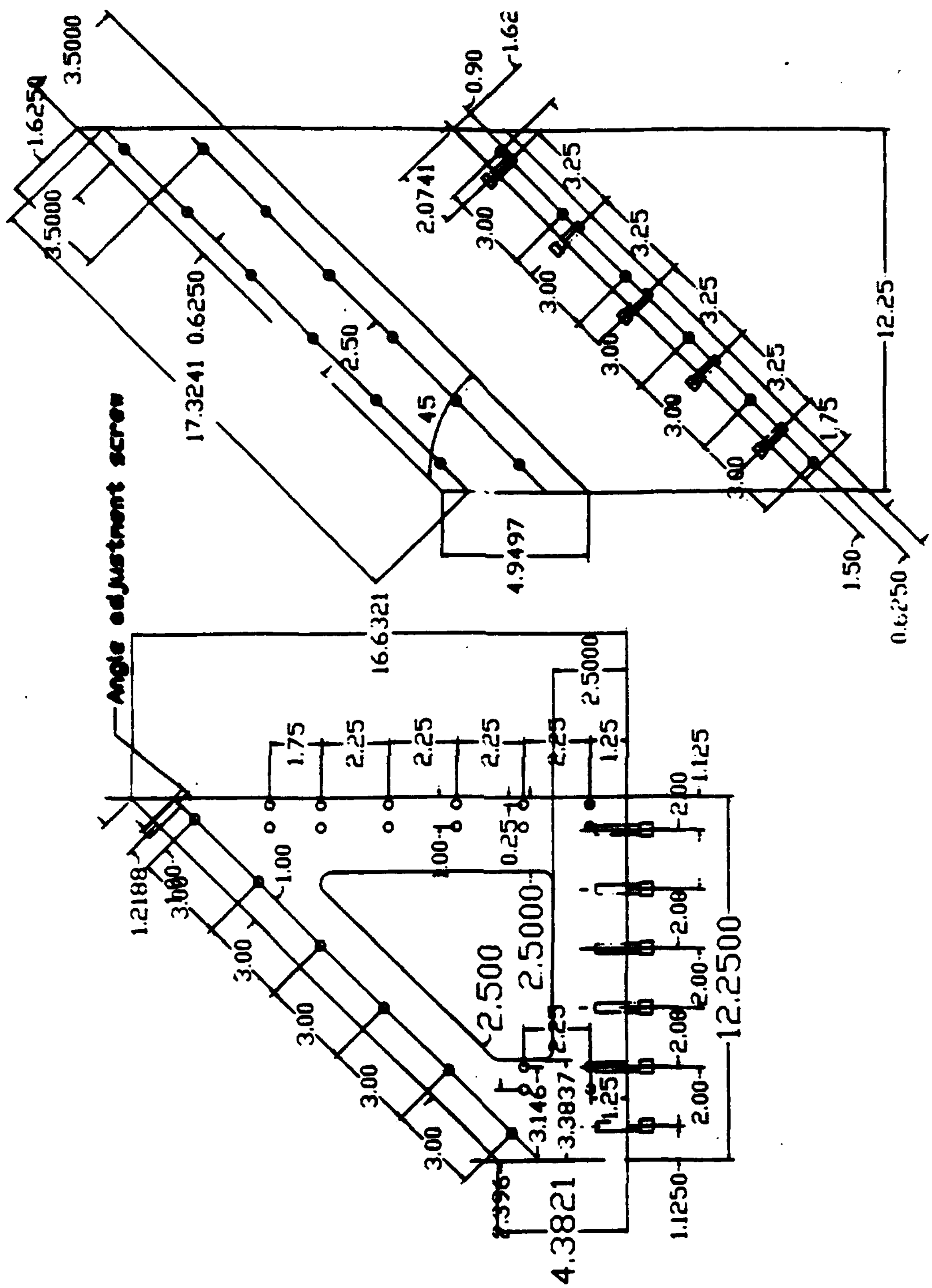

Figure C-5. Actuator #1 Supporting Plate

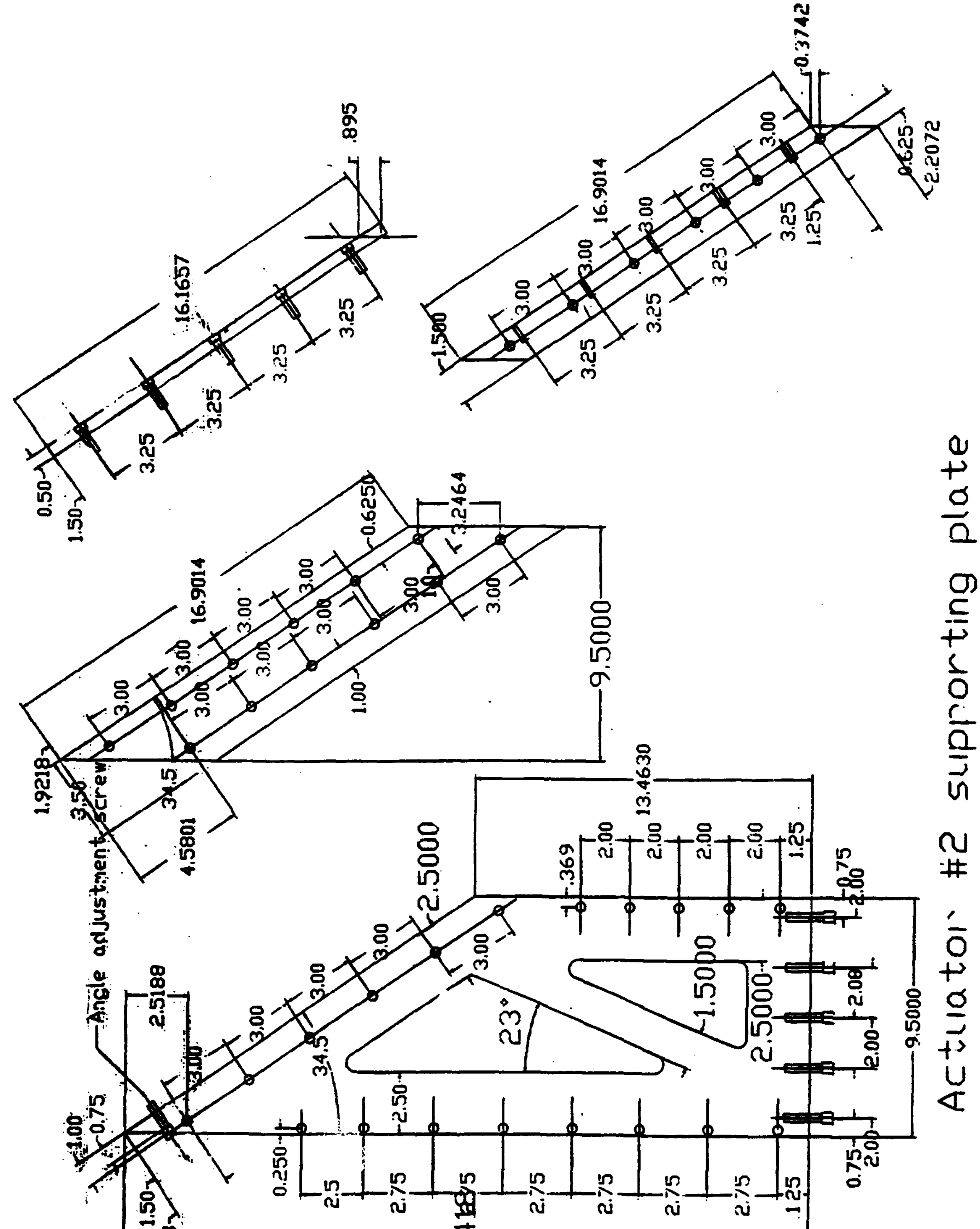

Figure C-6. Actuator #2 Supporting Plate

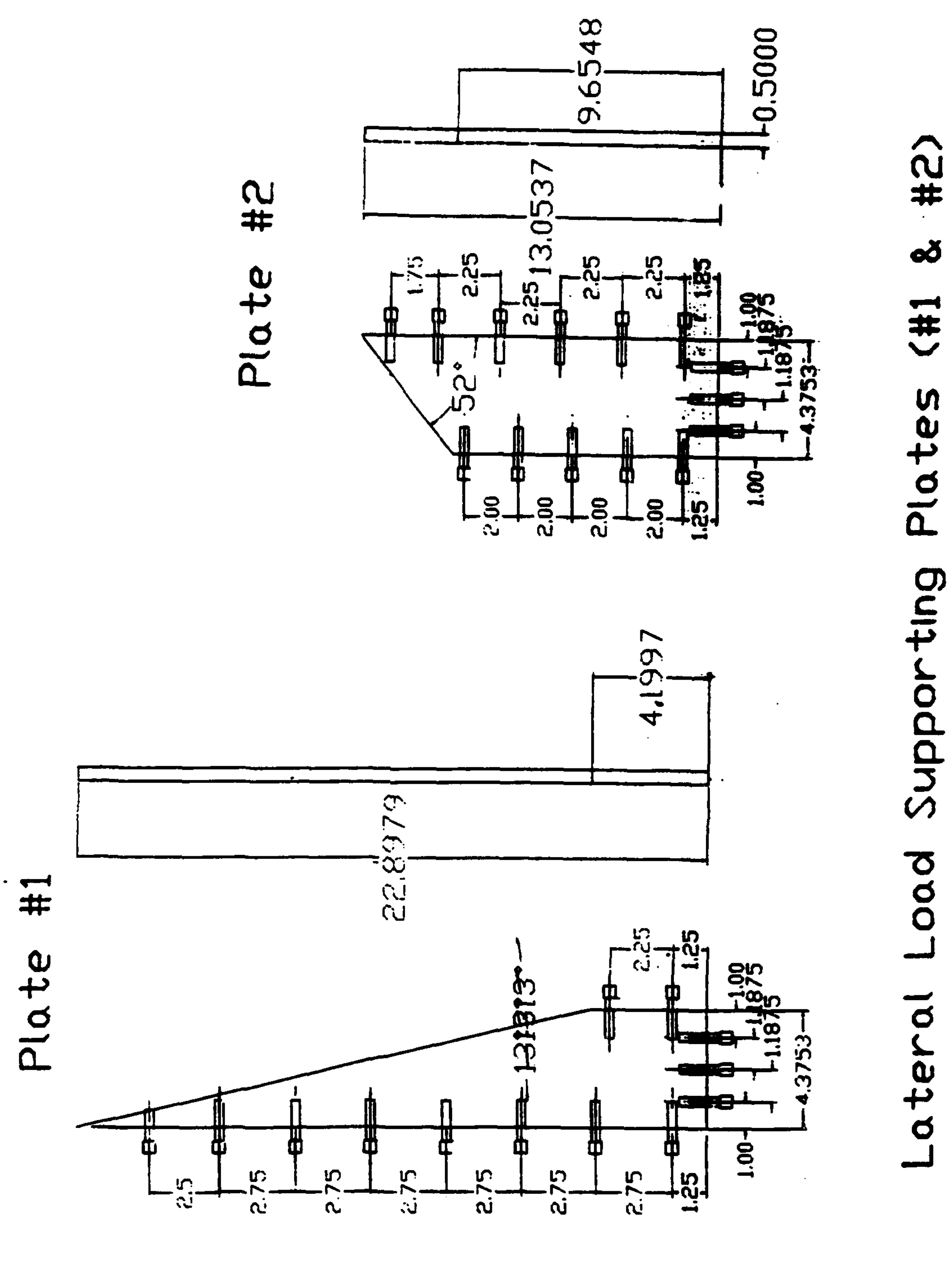

Figure C-7. Lateral Load Supporting Plates (#1 & #2)

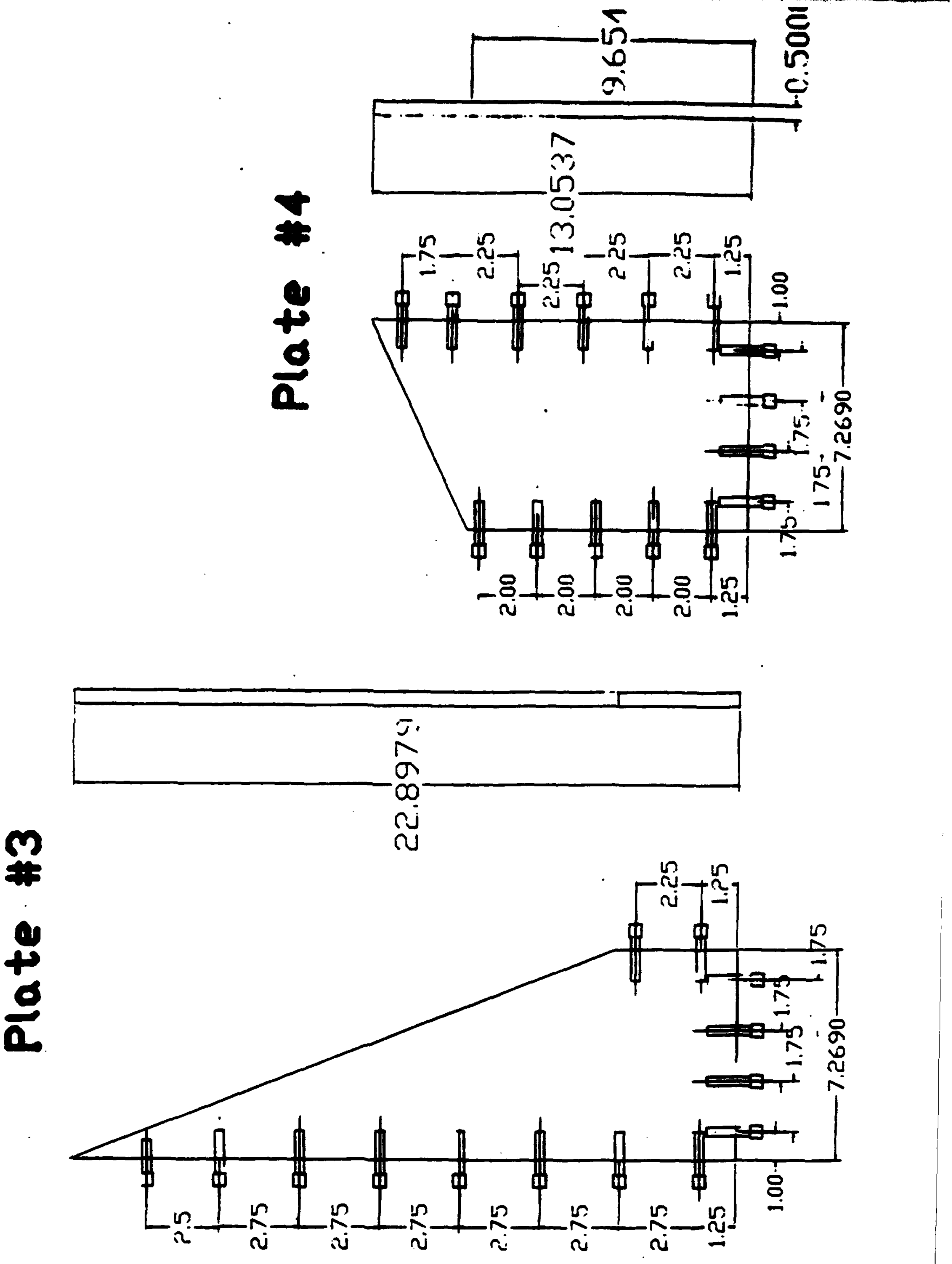

Figure C-8. Lateral Load Supporting Plates (#3 & #4)

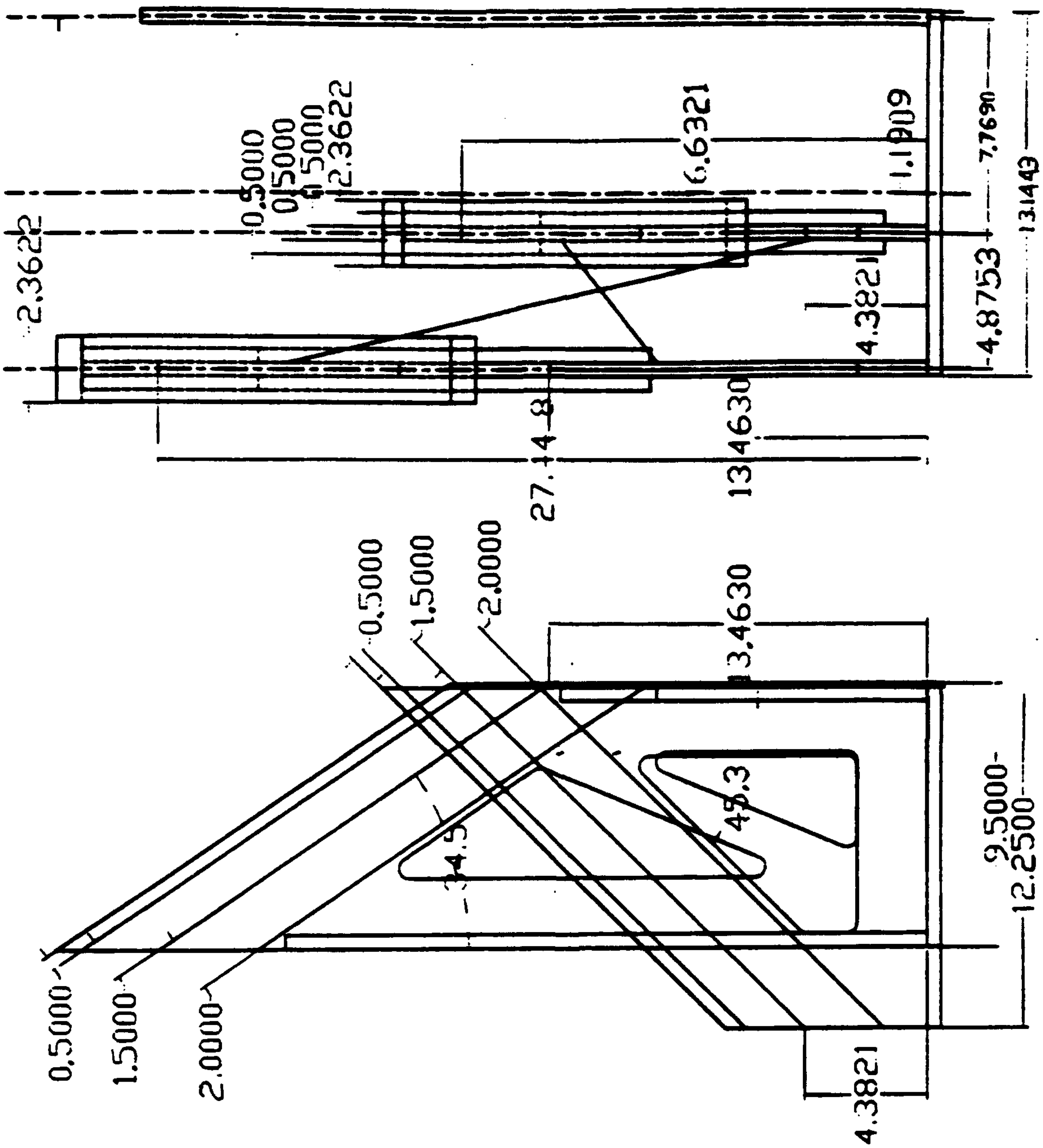

Figure C-9. Detail View of Base Assembly

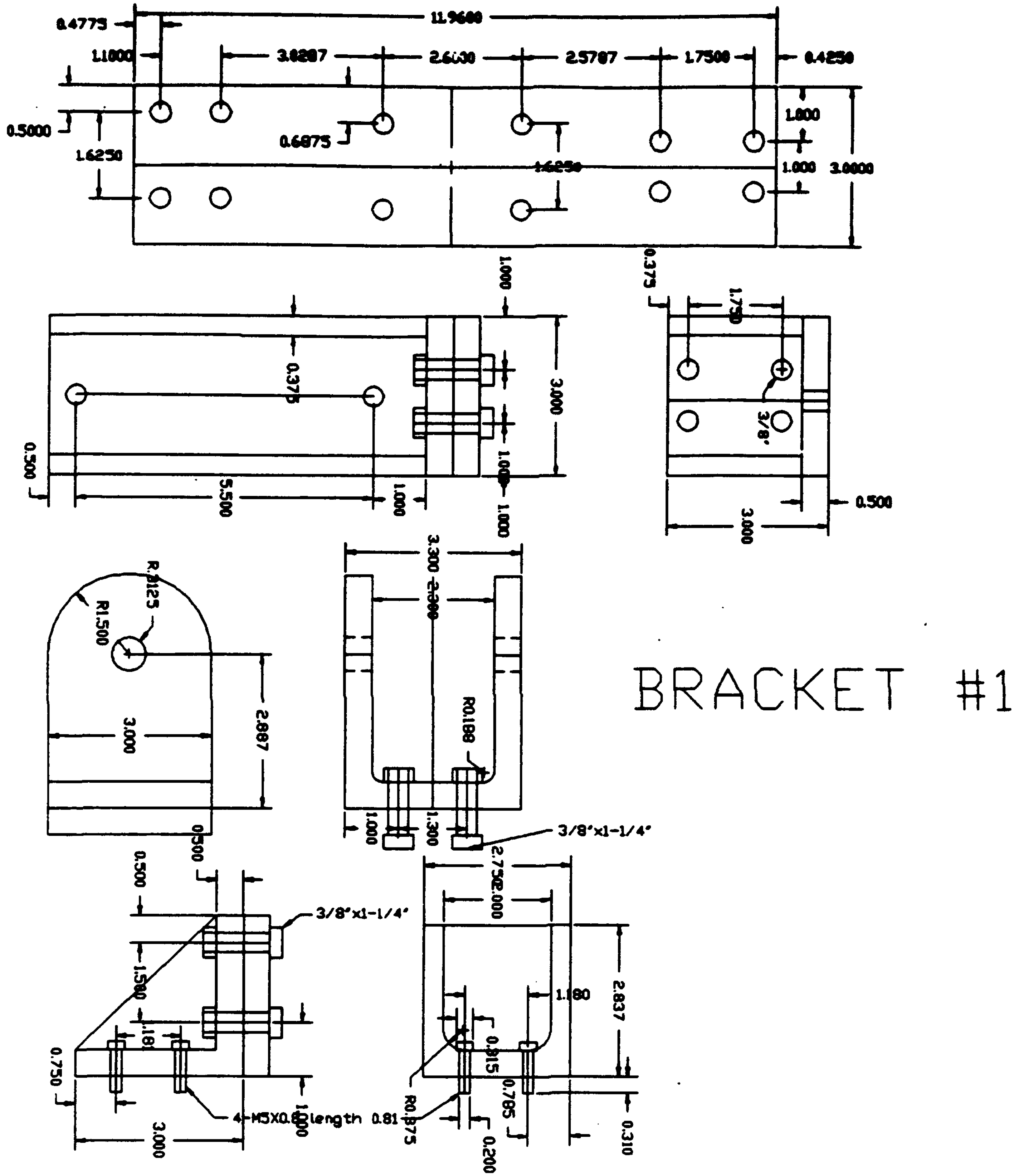

Figure C-10. Bracket #1

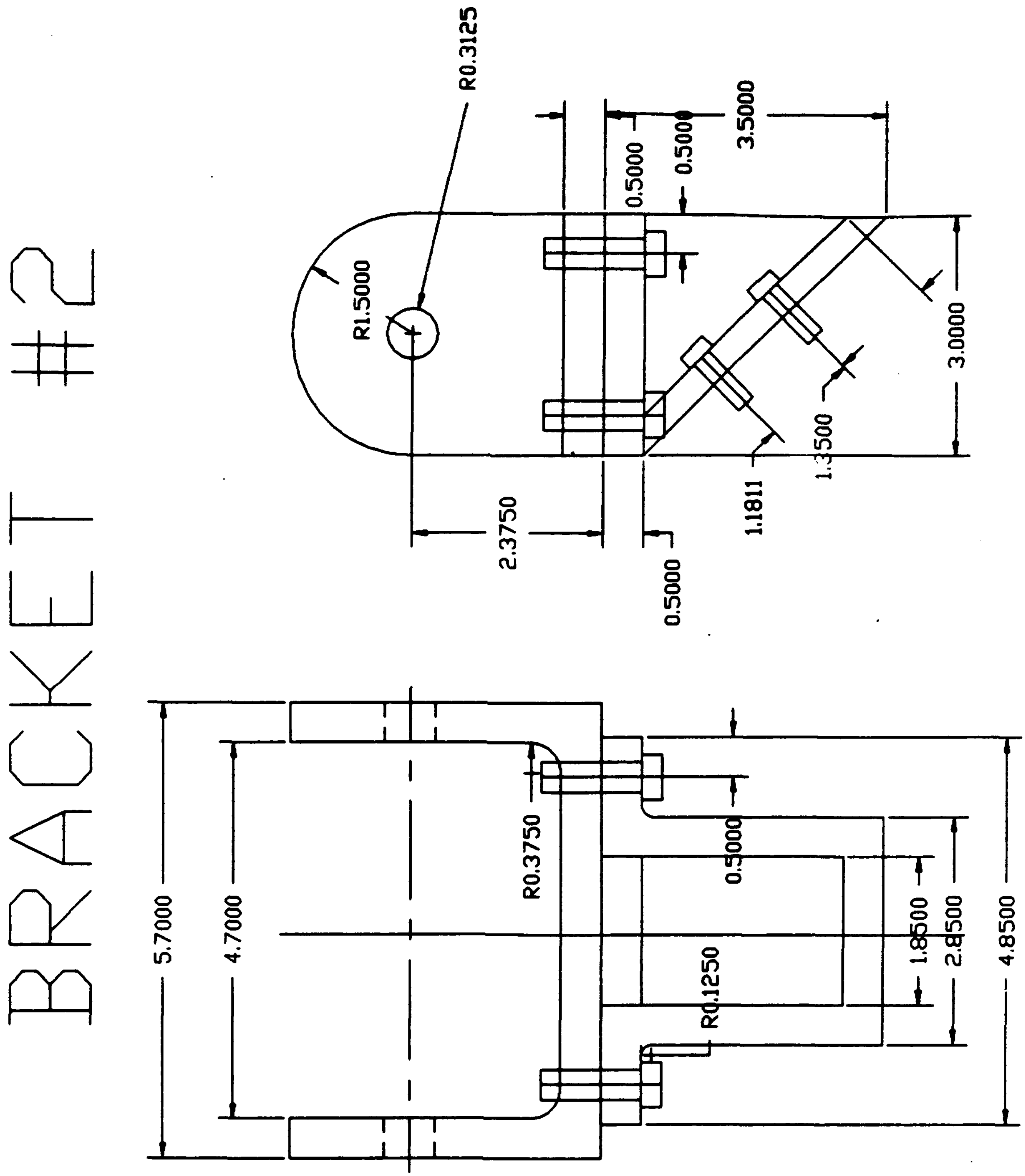

Figure C-11. Bracket #2

APPENDIX-D

CONTROLLER OF THE ROBOT

INTRODUCTION TO MOTION CONTROL

Motion control, in its widest sense, could relate to anything from a welding robot to the hydraulic system in a mobile crane. In the field of electronic motion control, systems falling within a limited power range, typically up to about 10 hp, and requiring precision in one or more aspects, are of primary interest. This precision requirement may involve accurate control of distance or speed, very often both, and sometimes other parameters such as torque or acceleration rate. In the case of the two examples given, the welding robot requires precise control of both speed and distance; the crane hydraulic system uses the driver as the feedback system so accuracy varies with the skill of the operator. A standard motion control system consists of three basic elements:

Motor: This may be a stepper motor(either rotary or linear), a dc brush motor or a brushless servo motor. The motor needs to be fitted with some kind of feedback device unless it is a stepper motor.

Drive: This is an electronic power amplifier which delivers the power to operate the motor in response to low-level control signals. In general, the drive will be specifically designed to operate with a particular type of motor.

Control System: The actual task performed by the motor is determined by the indexer/controller; it sets things like speed, distance, direction, and acceleration rate. The control function may be distributed between a host controller, such as a desk-top computer, and a slave unit which accepts high-level commands. One controller may operate in conjunction with several drives and motors in multiaxis systems.

Figure D-1 shows a system complete with feedback to control motor speed. Such a system is known as a closed loop velocity servo system.

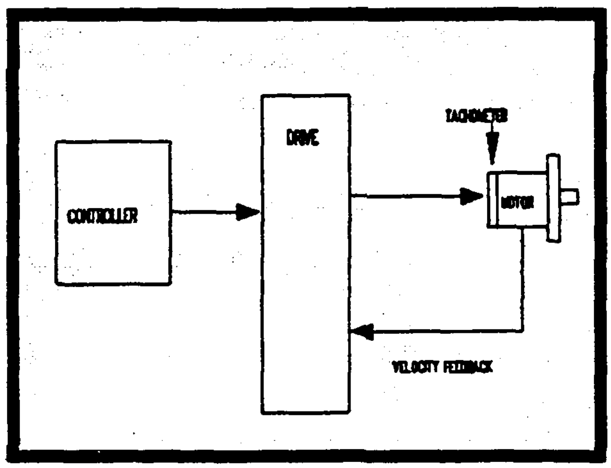

Figure D-1. Typical Closed Loop (Velocity) Servo System

HARDWARE

The equipment required to control the position of the manipulator was purchased from a combination of suppliers. First, three powerful servo motors were acquired from GEC ALSTHOM. These motors have a torque capacity of 500 oz.-in. and are packaged in a NEMA 34 frame size.

Next, providing the power to the motors is a three axis servo amplifier from Motion Science, Inc. The MHB 5020 MOSFET pulse width modulated switching amplifier was selected for its ability to provide the servo system with the peak motor power required when the maximum servo acceleration rate is used to reach maximum servo velocity. In addition to its ample power output, this amplifier offers flexibility and safety features. It is configurable as either a current(transconductance) amplifier for motor-encoder servos or as velocity control amplifier for motor-tachometer-encoder servos. Safety features include motor short protection, over/under voltage protection, and a user adjustable integrating current limiter.

Also from Motion Science, the MoPro II PC is a 80186, 16 bit, 16 MHz microprocessor based multiaxis motion and machine controller which is designed to be plugged into a personal computer(XT or AT) expansion slot. It can control any mix of one to six axis of servo and / or stepper motor all in coordinated path motion.

It receives acceleration, velocity, and position information in an ASCII format from the software, and uses that information to generate motion profile command signals for each axis. Move commands are sent to the driver in the form of step pulses at a rate of up to 500 kHz.

With simple indexer commands, the following moves can be performed with the MoPro II:

- Rotate the axis to a precise position and stop
- Rotate the axis at a constant velocity
- Alternate back and forth between two angular positions
- Use a sequential combination of these moves

The MoPro II can be used for precise position control with no external position feedback with open-loop control systems. However, an encoder interface is available for applications that require positional accuracy of the mechanical drive components (such as leadscrew drives on X-Y tables).

MOTION CONTROL SOFTWARE

Operation of the MoPro II is independent of the programming language used. The programmer need only have the means to read to and write from the I/O bus of the computer. Most programming languages have input and output procedures for this.

The MoPro II occupies four address locations on the computer bus. The control program writes commands to and reads data from registers at the base address. A register or buffer in this case refers to a temporary storage area for holding one character (or one eight bit byte). This transfer takes place one character at a time. Each character transfer requires that the program write control bytes to and read status bytes from a register at the address two values above the base address.

The basic algorithm for reading a character is as follows:

1. Read the byte from the register at address base + 2.

2. If bit number two is 1, then there is something in the message buffer.

3. If there is a message, then read a character from the register at the base address.

4. Repeat steps 1 through 3 until the character read is a null("\0").

Similarly, for writing a character:

1. Read the byte from the register at address base + 2.

2. If bit number one is 1, then the command buffer is full and will not accept more data.

3. If the bit is 0, a character may be written to the command buffer at the base address.

4. Repeat steps 1 through 3 until the entire command has been written, and then send a null to signal the end of the command.

A computer program written in C programming language was developed for this application. Although still in development, this program provides a graphic representation of the robot position at the end of each move, supports the use of a mouse, and includes at this time the following features:

- **Point and Shoot** - This subroutine allows the user to move the mouse cursor to position in the work envelope where he or she wishes the end effector to move and press either mouse button to accomplish the move.

- **Jog Axis** - As the name implies, choosing this option from the menu allows the user to move each actuator independently.

- **Run Routine** - This option allows the user to program a series of moves and to repeat this series any number of times.

- **Change Parameters** - With this command the user can easily vary such parameters as acceleration, velocity, position gain, and damping gain among others.

- **Access Card** - For the user fluent in MoPro II commands, this option provides direct communication with the controller.

APPENDIX-E

PUBLICATIONS

PUBLICATIONS

Published or Accepted Journal Papers:

1. **"On-Line Monitoring of Tool Breakage with Unsupervised Neural Networks,"** I.N. Tansel, C. McLaughlin, Transactions of the North American Manufacturing Research Institution of SME, May 1991, pp.364-370.

2. **"Automated Monitoring of Microdrilling Operations,"** I.N. Tansel, O. Rodriguez, Transactions of the North American Manufacturing Research Institution of SME, May 1992, pp. 205-210.

3. **"Modelling of 3-D Cutting Dynamics with Neural Networks,"** I.N. Tansel, Int. Jour. of Mach. Tools and Manufacturing, Vol.32, No.6, 1992, pp.829-853.

4. **"The Chaotic Characteristics of Three Dimensional Cutting,"** I.N.Tansel, C.Erkal, F. Karamidas, Int. Jour. of Mach. Tools and Manuf., Vol.32, No.6, 1992, pp.811-829.

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